Optimal Cell Connections for Improving Shading, Reliability, and Spectral Performance of Microsystem Enabled (MEPV) Modules

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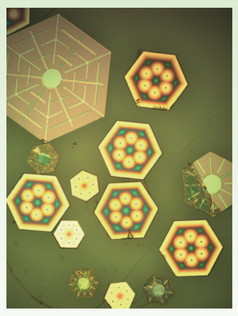
MEPV Concepts [1,2,7]

- Tiny (< 1mm), thin (20um) photovoltaic cells
- Tens to hundreds of thousands of cells/module
- Heterogeneously integrated multi-junction cells
- Micro-concentrating and Micro-tracking
- Potential integration on flexible substrates
- Potential integration with Electronics (Inverters, monitoring)



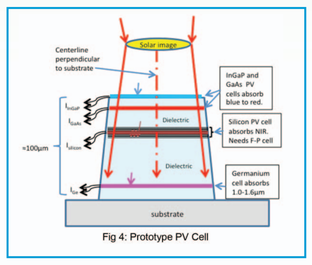
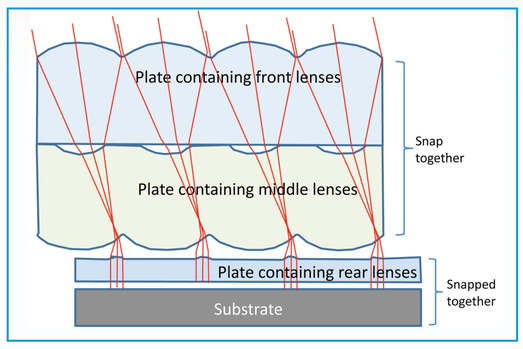
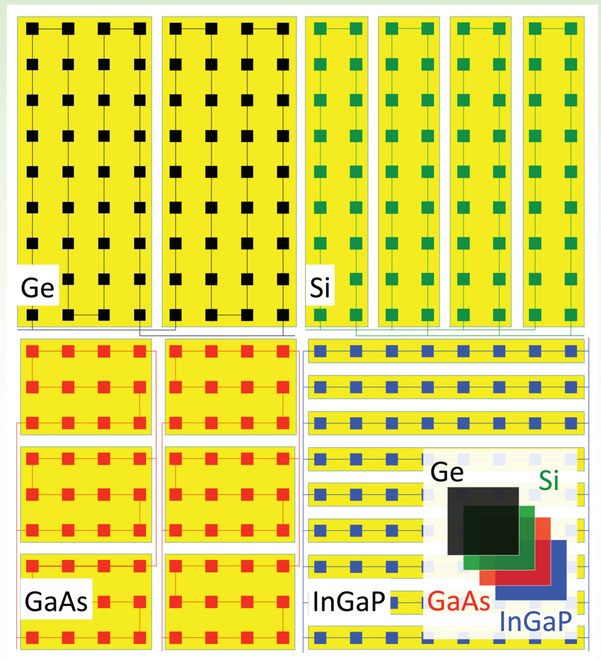


Fig 4: Prototype PV Cell



Pictures on left from reference 7

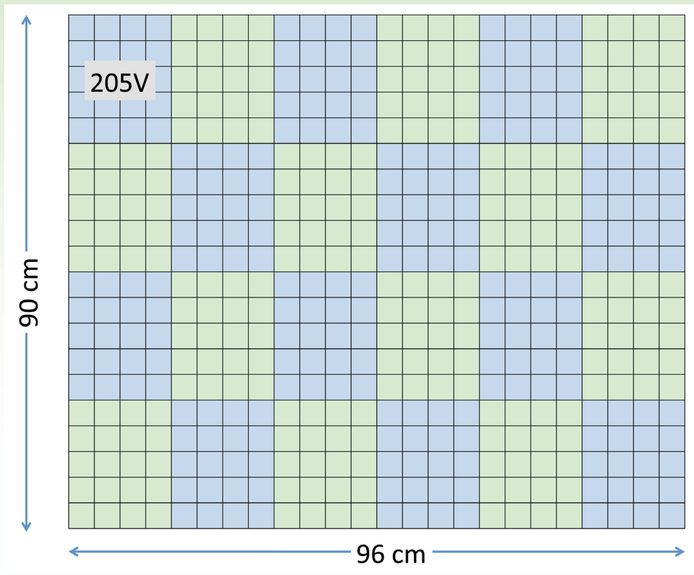
- Less Material, lower cost
- Easier thermal management
- High voltages in a small area =- tolerance to shading
- Parallel connected diodes – tolerance to spectral variations
- Lower balance of systems cost with high efficiency
- **How do you optimally connect 160,000 cells?**



Example connections of 72 stacked, 4 junction cells. The lower right shows a single stacked cell order (view from bottom).

In the rest of the figure, series connected diodes are shown in a yellow box; all yellow boxes are connected in parallel. The different cell types are stacked, not side-by-side.

Ge: 2 parallel groups of 36 series cells @ 0.30V (black);
Si: 4 parallel groups of 18 series cells @ 0.57V (green);
GaAs: 6 parallel groups of 12 series cells @ 0.9V (red);
InGaP: 9 parallel groups of 8 series cells @ 1.3V (blue)



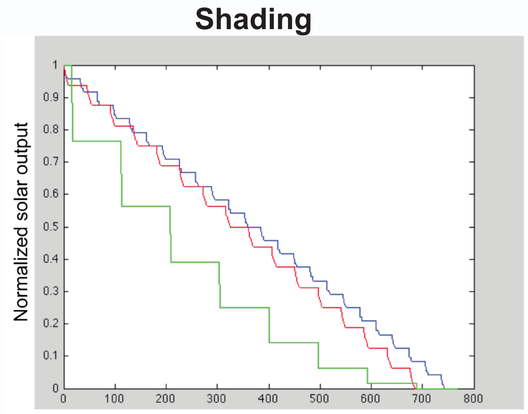
Module view: Each square above is a group of 72 cells of each type as illustrated on the left. Twenty groups of cells are connected in series to get a 'super-group' with a voltage of 205V as shown for example by the group of blue squares on the upper left. A 6 × 4 array of 'super-groups' are connected in parallel to comprise the module. The dimensions assume 5 mm cell spacing.

Cell Type	Bandgap	Operating Voltage	Series Cells	Ideal Voltage	Parallel Strings/ Group	Diodes per Group	Series Strings	Parallel Super-Groups	Module Cells
Ge	0.7	0.3	36	10.8	2	72	4 × 5	6 × 4	34560
Si	1.1	0.57	18	10.26	4	72	4 × 5	6 × 4	34560
GaAs	1.4	0.9	12	10.8	6	72	4 × 5	6 × 4	34560
InGaP	1.9	1.3	8	10.4	9	72	4 × 5	6 × 4	34560

For the three cases below:

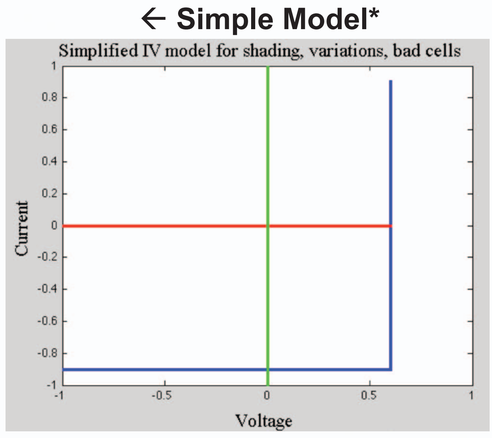
- **Diodes modeled as constant voltage and constant current**
- **All diode types nominally generated the same current**
- **Flat spectral Input**

Shading



Plot of the normalized solar output of four modules, each at 205V as described in the text, in both the x (red) and y (blue) directions as shading progresses in one dimension across the modules. The approximate performance of a conventional installation with ideal bypass diodes for each half module is shown in green.

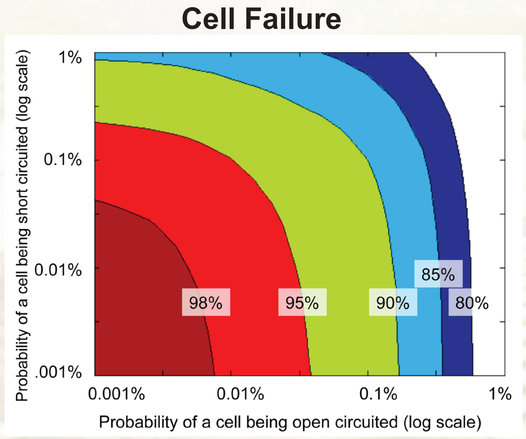
← Simple Model*



***Simple model applies to the simulations to the left and below, a more complex model is used for the spectral variations to the right. For the three cases below:**

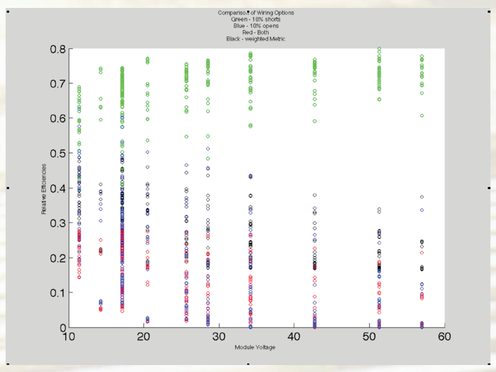
- **Cells modeled as constant voltage and constant current as below**
- **Single cell type (Si, V_{op}=0.57V)**

Cell Failure



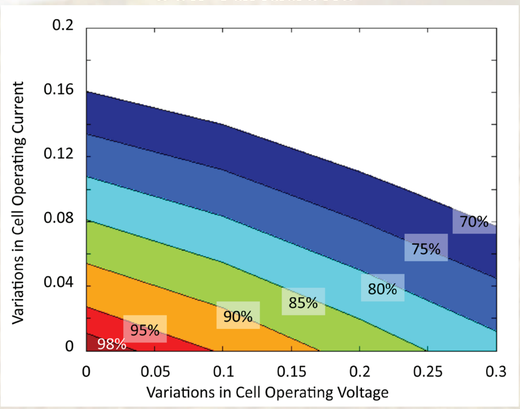
Simulated contour plot of the relative efficiency of the MEPV module as a percentage of a fully working module versus probability of a cell being open (x axis) or shorted (y-axis) for the modules described in the text, plotted on a log scale. Each of 256 data points (5 per decade) was calculated by averaging many (800) independent trials.

Connections



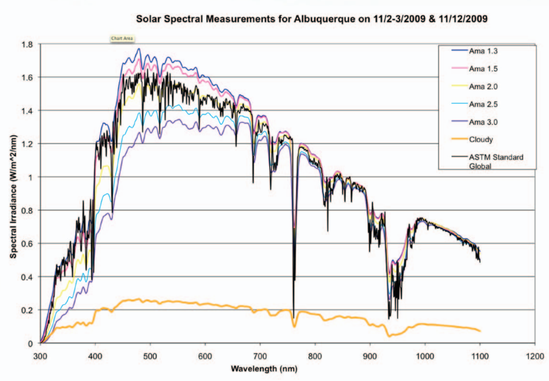
Simulated relative efficiencies (y-axis) for Si only MEPV modules consisting of 900 cells for 272 different cases for terminal voltages between 10V and 60V:
10% shorts and 0.1% opens (green)
10% opens and 0.1% shorts (blue)
10% opens and 10% shorts (red)
A weighted metric * (black)

Cell Variations

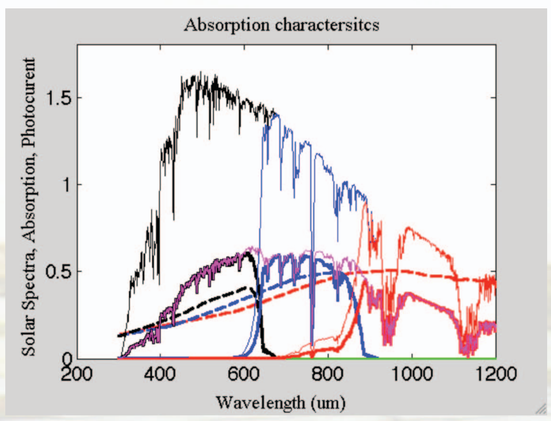


The x-axis is the standard deviation of the voltage, and the y-axis is the standard deviation in the current. The contours from 0,0 outward are 98%, 95%, 90%, 85%, 80%, 75%, and 70%. A 10% standard variation in current can lead to an 18% module degradation.

Spectral Variations

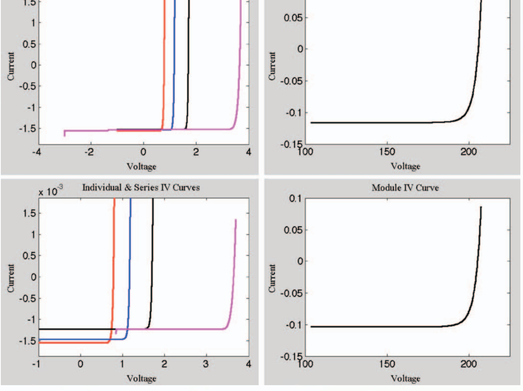


Spectra Used in the simulations



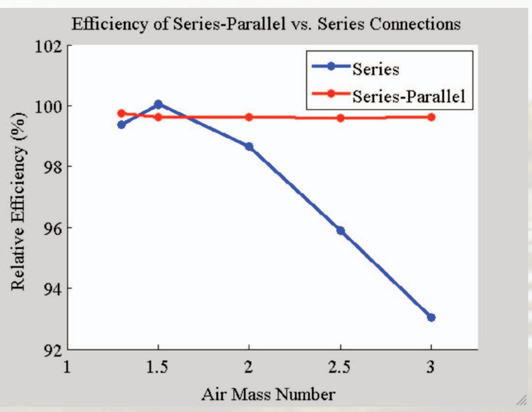
Incident AM1.5 light spectra and the portion absorbed by the InGaP (black), GaAs (blue), and InGaAs cells (top curves); their absorption (dashed curves) as a function of wavelength; and their contribution to the overall photocurrent (bottom solid curves). The magenta curve is the combined overall photocurrent contribution.

The absorption characteristics of the InGaP cell was approximated from shifted GaAs characteristics and the InGaAs cell used scaled Ge absorption characteristics.

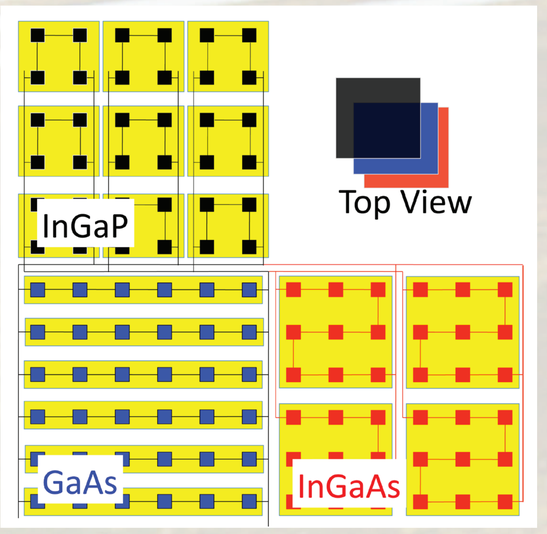


Individual diode IV curves in red (InGaAs), blue (GaAs), and black (InGaP) for AM1.5 (top-left) and AM3.0 (bottom-left). The structure diode parameters (thickness, surface recombination) were varied to match the efficiency of reference 6

The magenta curve is the series combination of the 3 curves. The curves on the right are the IV curves for a small module of the configuration shown below with 30 series groups for an operating voltage of ~ 192V.



IRelative module output power as a function of the spectrum on the input for the cases on the upper left.



Electrical Connections of cells within a 36-cell group of vertically stacked diodes for the example used for analysis of spectral variations.
InGaAs: 4 parallel groups of 9 series cells @ 0.70V;
GaAs: 6 parallel groups of 6 series cells @ 1.07V;
InGaP: 9 parallel groups of 4 series cells @ 1.59V;
Module Voltage is ~ 192V = 30 series groups x 6.4V

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